EO-1 Advanced Land Imager On-Orbit Radiometric Calibration

J. A. Mendenhall and D. E. Lencioni
MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420-9185, USA

Abstract - The Advanced Land Imager (ALI) is the primary instrument on the first Earth Observing Mission (EO-1), under NASA's New Millennium Program. On-orbit absolute radiometric calibration of this instrument relies primarily on solar calibration and involves pointing the ALI at the sun with the aperture cover closed; deploying a Spectralon diffuser over the secondary mirror; and exercising a variable area subaperture located in the cover. The bimonthly solar calibration data is supplemented by daily internal reference lamp observations, monthly lunar observations, and periodic observations of ground truth targets. Each of the above techniques will be reviewed and the results compared to prelaunch calibration parameters. Additionally, the stability of the ALI during the course of its first year on orbit will be presented.

INTRODUCTION

The primary goal of the Advanced Land Imager is to flight-validate emerging technologies so that they may be integrated into future Earth-observing instruments for a substantial mass, power, and cost savings, while acquiring high-quality data [1,2]. The validation of these technologies hinges on flight data that is accurately calibrated. Launched on November 21, 2000, the ALI collected several calibration data sets during the first year of operations on-orbit in order to verify the performance of the instrument. This paper provides an overview of the on-orbit radiometric performance assessment of the ALI based on these data and compares results with those obtained during preflight calibration.

RADIOMETRIC CALIBRATION TECHNIQUES

The radiometric response of the ALI is a function that is applied to each detector in order to transform the digital response of the instrument (DN) into scientific units (e.g. $mW/cm^2/sr/\mu m$). The usefulness of a response function is based on its accuracy, when comparing calibrated instrument data to scenes with independently known radiances. The radiometric response of the ALI was extensively calibrated at Lincoln Laboratory before integration with the spacecraft and is discussed elsewhere [3]. The response of the instrument was also calculated on orbit using data from four independent calibration sources: solar, lunar, ground truth, and internal reference lamps. These data are used to determine if any changes in the response of the instrument occurred during integration and testing at the spacecraft level or during launch as well as monitor the instrument's stability on orbit.

Solar Calibration

Solar calibration of the ALI is conducted approximately every fourteen days on-orbit. The solar calibration procedure, which is illustrated in Figure 1, involves pointing the ALI at the Sun with the aperture cover closed. A motor-driven aperture selector in the aperture cover assembly moves an opaque slide over a row of small to increasingly larger slit openings and then reverses the slide motion to block all sunlight. Just prior to solar calibration, a space grade Spectralon® diffuser plate is swung over the secondary mirror by a motor-driven mechanism. The diffuser reflectively scatters the sunlight that would otherwise impinge on the secondary mirror. The scattered sunlight exposes the FPA to irradiance levels equivalent to earth-reflected sunlight for albedos ranging from 0 to 100% [4].

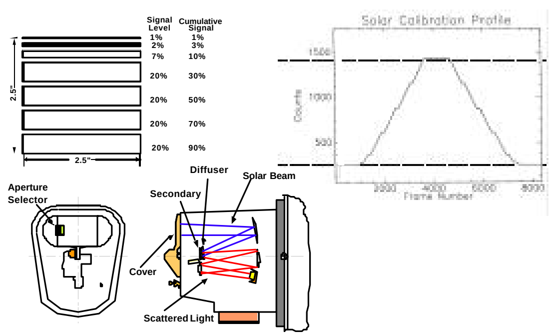

Fig. 1. Illustration of the solar calibration mode and laboratory test data from a solar simulator.

The absolute radiometric calibration of the ALI, derived from pre-flight measurements, is checked by comparing the expected radiance observed for level 6 of the solar calibration to the observed radiance.

Ground Truth

The second method of assessing the radiometric accuracy of ALI data hinges on reflectance-based ground truth measurements. The principle of this technique is to image a stable, high-altitude, flat, diffuse ground target using the ALI while ground teams simultaneously measure the reflective properties of the target region and local atmospheric conditions. The ground measurements can then be used to predict the top of the atmosphere radiance observed by the ALI.

Throughout the first year of the EO-1 mission, ground truth campaigns were conducted by several groups, including the University of Arizona, the University of Colorado, the Australian CSIRO, and the NASA Jet Propulsion Laboratory. Ground truth sites include Barreal Blanco and Arizario Argentina, Lake Frome Australia, and complementary sites in the western United States (Railroad Valley, Ivanpah Playa, Walnut Gulch, and White Sands).

Lunar Calibration

The lunar radiometric calibration method involves observing the Moon with the instrument and comparing the measured lunar irradiance with a predicted lunar irradiance for the time of the observation.

Lunar observations using the ALI have been conducted near a 7° phase angle each month since January 2001. For each observation, the spacecraft is maneuvered to scan the Moon in the in-track direction at 1/4 the nominal scan rate. To calculate the observed lunar irradiance, dark current levels are subtracted and the image is radiometrically calibrated using the pre-flight calibration coefficients. A region of interest, narrowly circumscribing the Moon, is then defined by locating the region of each column where the intensity falls to below 1% of the average lunar irradiance (Figure 2). Summing the response within the circumscribed region, the spectral irradiance of the Moon for each band may be calculated as

$$\AA_M(\ddot{e}) = \frac{d\Theta\Delta}{fF}\Sigma L_P(\,l\,)$$

Here, E_M (λ) is the lunar spectral irradiance, $d\Theta$ is the ALI pitch rate during the scan (radians/second), Δ is the detector pitch (μm), f is the ALI focal length (m), F is the frame rate (Hz), and L_P (λ) is the measured lunar spectral radiance for detector P (mW/cm^2/sr/μm).

Once the lunar irradiance has been calculated for a given observation, the expected lunar irradiance for the time of the observation is calculated by the USGS using data obtained from the robotic lunar observatory (ROLO) in Flagstaff Arizona [5]. Since 1996, ROLO has been measuring the lunar irradiance between 350 and 2500 nm as a function of phase angle as often as weather and seeing permit. The USGS has been able to use this database to predict lunar irradiances for most phase angles. As a result, lunar observations are emerging as an exciting new opportunity for radiometric calibration of space based VNIR/SWIR instruments.

Fig. 2. Image of the Moon taken by the ALI on February 7, 2001. The circle surrounding the Moon describes the regions used in the lunar irradiance calculations.

Internal Reference Lamp Illumination

An internal reference source, mounted on the optical metering truss, is used to monitor the radiometric stability of the ALI on-orbit. This source consists of three Welch Allyn 997418-7 (modified) gas-filled lamps mounted on a small (2.03 cm) diameter integrating sphere. Light emerging from the exit port of the sphere passes through a BK 7 lens and spectral-balancing filter, is reflected off the ALI flat mirror (M4), and floods the focal plane.

The internal reference lamps are activated during two data collection events per day, when the ALI aperture cover is closed. After an eight-second stabilization period the lamps are sequentially powered down in a staircase fashion, with two-second exposures between each step. In this manner, the focal plane will receive a daily three-point radiometric reference.

Initially, the internal reference source was to serve as a radiometric transfer standard between pre-flight and on-orbit calibrations of the ALI. However, a noticeable increase in lamp output in the VNIR was observed immediately after launch. This has been attributed to a loss of convective cooling of the filament in the zero-G environment. This increase in lamp output has resulted in invalidating attempts at using the reference lamps as a calibration transfer standard between preflight and flight calibration of the ALI detector arrays. However, the lamp output has been very repeatable since launch and has proven to be invaluable at monitoring the stability of the focal plane during the first year of on-orbit operations.

ON-ORBIT/PRE-FLIGHT CALIBRATION COMPARISON

The February 8, 2001 solar calibration data for aperture selector position six have been normalized to the expected values and are presented in Fig. 3. These data are plotted at the mean wavelength of each band (Table 1 provides a listing the ALI spectral bands and associated mean wavelengths). With the exception of band 1p, the solar and pre-launch calibrations agree to within the estimated uncertainties. The pre-launch calibration accuracy combined with the additional on-orbit effects of contamination and stray light is estimated to be less than 5% for all bands. The solar calibration uncertainty is estimated to be 5% in the VNIR bands and 7% in the SWIR bands. The larger uncertainty in the SWIR bands is due to both the uncertainty in the solar irradiance models and the BRDF of the Spectralon. The low response in band 1p is a significant discrepancy between the two calibration techniques.

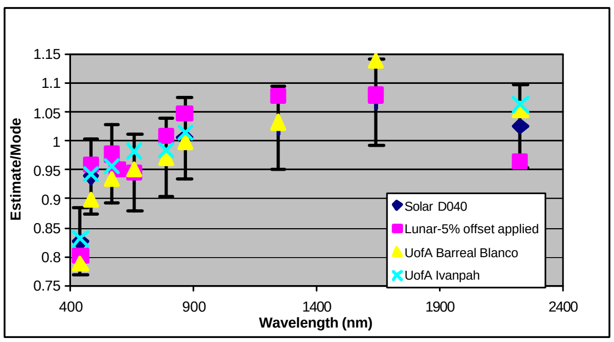

Fig. 3: Results from solar, ground truth, and lunar absolute radiometric calibrations.

Table 1
ALI Spectral Bands

Band	Mean Wavelength (nm)
1p	442
1	485
2	567
3	660
4	790
4p	866
5p	1244
5	1640
7	2226
Pan	592

Ground truth measurements of Barreal Blanco, Argentina and Ivanpah Playa, California obtained by the Remote Sensing Group of the University of Arizona are also presented in Figure 3. The errors associated with the ground truth measurements have been estimated to be ±3% [6].

Clearly, the ground truth and solar calibration measurements agree for most bands. The repeatability of the Band 1p offset and overall trend in the VNIR add confidence to the solar calibration model and indicates a change in the ALI radiometric response since pre-flight calibration for these bands. However, a 7% difference between the solar and ground truth data exists for Band 5 and is not well understood at this time.

The results of a lunar irradiance comparison for measurements obtained on February 7, 2001 required a normalization of 5% to the ROLO data for all bands in order to bring the results into agreement with ALI measurements. The source of this offset is unclear at this time and is continuing to be investigated. However, once the 5% offset is applied, the lunar irradiance comparison result was overlaid with solar and ground truth comparisons in Figure 3. The lunar data agree well with the other techniques, supporting the hypothesis that the radiometric response of the instrument has changed significantly for Band 1p and has drooped slightly in the VNIR since pre-flight measurements were taken.

Extensive investigations into the discrepancy between preflight and flight radiometric response measurements have been conducted at the Laboratory and the most likely sources of these effects are changes in the reflectivities of the mirrors or bandpasses of the spectral filters. Internal reference lamp trending indicates the reflectivity of flat mirror (M4) and the response of the focal plane has remained stable to within 1% for bands 1p, 1, 2, 5p, 5, 7, pan, and within 3% for bands 3, 4, 4p since launch. Unfortunately, the observed increase in internal lamp intensity after launch prohibits one from extending focal plane response trending from preflight calibration to on orbit. However, trending does exist from preflight calibration at Lincoln Laboratory in December 1998 through the second spacecraft thermal vacuum test at Goddard Space Flight Center in July 2000 (4 months before launch). This data indicates M4 and the focal plane have remained stable to within 2% during ground testing. Furthermore, solar, lunar, and ground truth data trending, which exercise other elements of the optical train, suggest M1, M2, M3, and the solar diffuser have been stable to within 1% since the first on-orbit calibrations in late December 2000. As a result, if a response change did occur within the instrument, it must be restricted to between July 2000 and November 21, 2000 if the change occurred on M4 or the focal plane or it must be restricted to between December 1998 and December 29, 2000 if the change occurred on M1, M2, or M3.

Radiometric Stability

The radiometric stability of the ALI has been tracked since launch using the techniques outlined above. Solar calibrations occur every two weeks and began on January 9, 2001. Lunar calibrations occur monthly and began on January 28, 2001. Ground truth measurements occur approximately every 2 months and began on December 29, 2000. Internal reference lamp measurements have been taken daily since November 25, 2000. However, only internal lamp measurements taken one day after focal plane bakeouts are used in stability analyses.

The stability data from all of the techniques described above for Band 3 have been overlaid in Figure 4 as an example. Stability data indicate the instrument has been stable to within 1% for Bands 1p, 1, 2, 5p, 5, 7, pan and within 3% for Bands 3, 4, 4p since launch. Linear fits to the solar and internal lamp data are also overlaid. Table 2 tabulates stability results for each band.

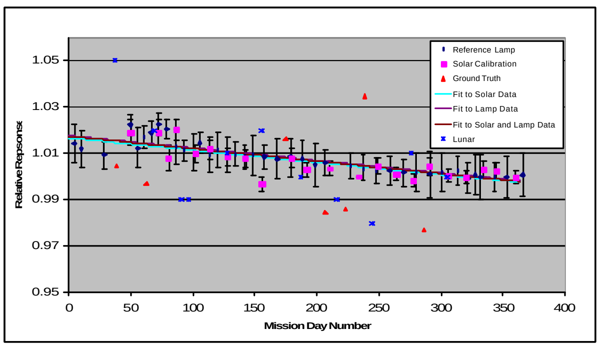

Fig. 4. Radiometric stability for Band 3 during the first year on orbit.

TABLE 2
Radiometric stability trending.

Band	Response Change (%/year)
1p	-0.8
1	-0.7
2	-0.9
3	-2.5
4	-2.6
4p	-2.7
5p	-0.8
5	-0.8
7	-0.7
Pan	-0.8

Conclusion

Although the cause of the preflight to flight radiometric calibration discrepancy is not clearly understood, good agreement between solar, lunar and ground truth measurements, and excellent stability of the instrument suggests a single radiometric correction to the preflight calibration coefficients for each band will provide ±5% agreement between measured solar, lunar and ground truth data and expected values (Table 3). These factors have been used to update the preflight radiometric coefficients residing in the EO-1 ALI Radiometric Calibration Pipeline.

TABLE 3
Radiometric correction factors.

Band	Correction Factor
1p	1.21
1	1.07
2	1.05
3	1.04
4	1.02
4p	0.99
5p	0.98
5	0.87
7	0.98
Pan	1.05

References

[1] J. A. Mendenhall et al., “Earth Observing-1 Advanced Land Imager: Instrument and Flight Operations Overview,” MIT/LL Project Report EO-1-1, 23 June 2000.
[2] D. R. Hearn, et al., “EO-1 Advanced Land Imager Overview and Spatial Performance,” IGARSS, Sydney, Australia, 9 July 2001.
[3] J. A. Mendenhall, D. E. Lencioni, J. B. Evans, "Earth Observing-1 Advanced Land Imager: Radiometric Response Calibration," MIT/LL Project Report EO-1-3, 29 November 2000.
[4] D. E. Lencioni, J. A. Mendenhall, D. P. Ryan-Howard, “Solar Calibration of the EO-1 Advanced Land Imager,” IGARSS, Sydney, Australia, 9 July 2001.
[5] Keiffer, H.H, Anderson, J.A., “Use of the Moon for spacecraft calibration over 350-2500 nm”, Proc. SPIE, 2438, 325-335, 1998.
[6] Bigger, S. F., Private Communication, May 2001.

This work was sponsored by NASA/Goddard Space Flight Center under U.S. Air Force, Contract F19628-00-C-0002.

Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.